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Coded MB-OFDM UWB**

Zixuan Lin  
*University of Wollongong, [zl715@uowmail.edu.au](mailto:zl715@uowmail.edu.au)*

Le C. Tran  
*University of Wollongong, [lctran@uow.edu.au](mailto:lctran@uow.edu.au)*

Farzad Safaei  
*University of Wollongong, [farzad@uow.edu.au](mailto:farzad@uow.edu.au)*

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## Order-4 orthogonal cooperative communication in Space-Time-Frequency Coded MB-OFDM UWB

### Abstract

The combination of cooperative communication and Space-Time-Frequency-Codes (STFCs) has been recently proposed in the literature for Multiband OFDM Ultra-Wideband (MB-OFDM UWB) to improve the bit error performance, system capacity, data rate and wireless communications range. This paper proposes a cooperative communication design using Order-4 Orthogonal STFCs in MB-OFDM UWB systems, which is referred to as Order-4 Orthogonal Cooperative Communication Scheme (4-OCCS). It will be shown that 4-OCCS improves significantly the diversity and error performance of the MB-OFDM UWB system, compared to the conventional MB-OFDM UWB (without STFCs) as well as our Order-2 Orthogonal Cooperative Communication Scheme using Alamouti STFCs (2-OCCS) proposed previously, with the same data rate and without any increase of transmission power.

### Keywords

time, uwb, coded, ofdm, frequency, order, 4, orthogonal, cooperative, communication, space, mb

### Disciplines

Engineering | Science and Technology Studies

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# Order-4 Orthogonal Cooperative Communication in Space-Time-Frequency Coded MB-OFDM UWB

Zixuan Lin, Le Chung Tran and Farzad Safaei

Faculty of Informatics  
University of Wollongong, Australia  
{zl715,lctran,farzad}@uow.edu.au

**Abstract**—The combination of cooperative communication and Space-Time-Frequency-Codes (STFCs) has been recently proposed in the literature for Multiband OFDM Ultra-Wideband (MB-OFDM UWB) to improve the bit error performance, system capacity, data rate and wireless communications range. This paper proposes a cooperative communication design using Order-4 Orthogonal STFCs in MB-OFDM UWB systems, which is referred to as Order-4 Orthogonal Cooperative Communication Scheme (4-OCCS). It will be shown that 4-OCCS improves significantly the diversity and error performance of the MB-OFDM UWB system, compared to the conventional MB-OFDM UWB (without STFCs) as well as our Order-2 Orthogonal Cooperative Communication Scheme using Alamouti STFCs (2-OCCS) proposed previously, with the same data rate and without any increase of transmission power.

## I. INTRODUCTION

Combination of the emerging technologies, namely Orthogonal Frequency Division Multiplexing (OFDM), Multiple Input Multiple Output (MIMO), and Space-Time Codes (STCs), which is referred to as MIMO-OFDM, may provide a significant improvement in bit error performance, system capacity, data rate and the maximum achievable wireless communications range [1],[2],[3]. While this combination for ordinary OFDM systems has been intensively examined, the combination of Multiband OFDM Ultra-Wideband (MB-OFDM UWB) [4], MIMO and STCs has not been so widely examined, with few publications, such as [5] and [6].

The main differences between a conventional OFDM system and a MB-OFDM UWB one can be concluded in the following two aspects. First, channels in the latter are much more dispersive than those in the former, with the average number of multipaths in some channel models reaching some thousands [7]. Second, channel coefficient in the former are usually considered as Rayleigh distributed random variables, while those in the latter are log-normally distributed [7]. Therefore, the systems incorporating MB-OFDM UWB, MIMO and STCs must be more specifically analyzed, though there exist several similarities between those systems and the conventional MIMO-OFDM ones.

To increase further the system diversity order, Space-Time-Frequency Codes (STFCs) have been proposed for MB-OFDM UWB systems in our previous works, where individual symbols in the conventional Space-Time-Block Codes (STBCs), such as the Alamouti code [14], are replaced by OFDM symbols. Interested reader can refer to our previous

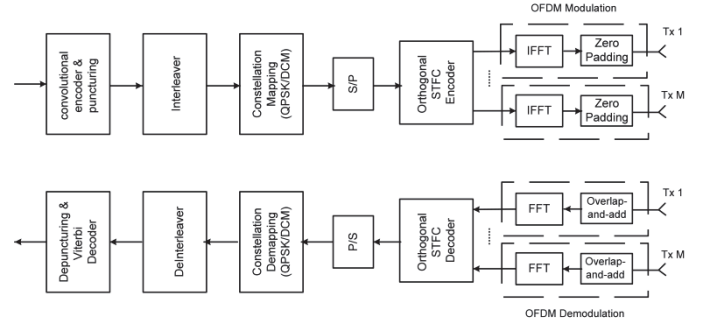


Fig. 1. Structural diagram of the proposed STFC MB-OFDM UWB system [6]

works [6], [8], [9] for the framework of STFC MB-OFDM UWB systems for multiple number of transmit/receive (Tx/Rx) antennas.

However, the MIMO STFC MB-OFDM UWB systems proposed in [6], [8], [9] must have multiple antennas at the transmitter, as depicted in Fig.1. In fact, the source node (i.e. the transmitter, such as portable devices) may only be equipped with a single antenna due to their tiny physical size, which does not facilitate the space of at least a half wavelength to install two uncorrelated Tx antennas. Cooperative communication concept has been introduced to the source nodes to create a virtual MIMO system in such a way that the proposed STFCs and MIMO concept can still be implemented in the MB-OFDM UWB system and thus a large diversity order can still be achieved. Though cooperative communication has been intensively examined for general wireless networks in the literature, such as [10], [11], [12], it has been almost unexplored for MB-OFDM UWB. In [13], we proposed an order-2 orthogonal cooperative communication scheme (2-OCCS) for the STFC MB-OFDM system using the Alamouti STFC [6], which is, in turns, the modified version of the Alamouti code [14], for only two source nodes. The results show that the combination of cooperative communication and STFC MB-OFDM UWB is able to gain benefits from MIMO system and improve significantly the performance of the conventional MB-OFDM UWB system.

A drawback of the aforementioned Alamouti STFC is that it cannot be used for more than two cooperative nodes. A question that could be raised is whether it is possible for more than two source nodes (up to four nodes for instance) to collaborate in the cooperative STFC MB-OFDM UWB system. Resolution for this question would be very useful, since it might

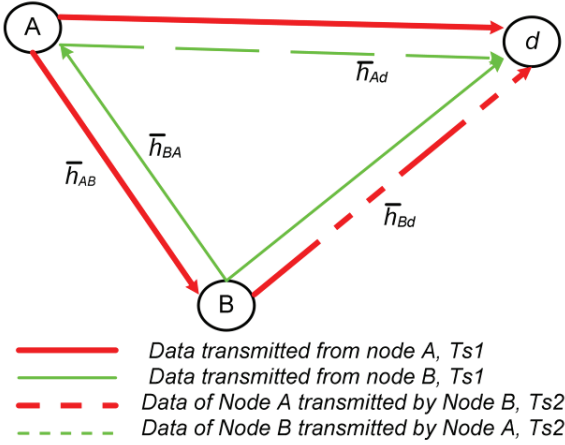


Fig. 2. Cooperative communication using Alamouti STFC in MB-OFDM UWB between the source nodes  $A$ ,  $B$  and the destination  $d$ .

allow the hybrid cooperation scheme with a flexible selection of two, three and up to four cooperative nodes. This paper thus proposes the cooperative scheme for four source nodes through the application of an order-4 Orthogonal Space-Time Frequency Code (OSTFC), which is the modified version of the conventional order-4, rate-3/4 STBC proposed in [16], to the MB-OFDM UWB system. The higher-order OSTFC offers a greater diversity with the cost of having a smaller code rate. In this paper, we propose an order-4 orthogonal STFC cooperative communication scheme, referred to as 4-OCCS hereafter. The new subband allocation technique for the proposed system will then be introduced. The error performances of the 2-OCCS and 4-OCCS schemes are compared in several scenarios to verify in which scenario the application of cooperative communication is useful for STFC MB-OFDM UWB.

The paper is organized as follows. Section II briefly reviews our 2-OCCS proposed in [13]. Section III presents the proposed 4-OCCS. Simulation results are shown in Section IV and Section V concludes the paper.

*Notations:* The following notations will be used throughout the paper. The superscripts  $(\cdot)^*$  and  $(\cdot)^T$  denote the complex conjugation and transposition operation, respectively. We denote  $\bar{a} \bullet \bar{b}$  to be the element-wise (or Hadamard) product of the two vectors  $\bar{a}$  and  $\bar{b}$ .  $N_D$  and  $N_{fft}$  are the number of data subcarriers and the FFT/IFFT size, respectively (for MB-OFDM UWB communications [6],  $N_D = 100$  and  $N_{fft} = 128$ ). Further,  $\bar{a}^{\wedge 2}$  denotes the element-wise power-2 operation of  $\bar{a}$ . The complex space  $C$  of a symbol  $s$  denotes all potential possibilities that the symbol  $s$  can take, while the  $N_D$  dimensional complex space  $C^{N_D}$  of a  $N_D$ -length vector  $\bar{s}$  denotes all potential possibilities that the vector  $\bar{s}$  can take. We define  $\bar{1}$  as a column vector of length  $N_D$ , whose elements are all 1. We denote  $\|\cdot\|_F$  to be the Frobenius norm. Finally, we refer the time required to transmit a MB-OFDM symbol to as a MB-OFDM symbol time slot.

## II. ORDER-2 ORTHOGONAL COOPERATIVE COMMUNICATION SCHEME USING ALAMOUTI STFC (2-OCCS)

This section briefly reviews the cooperative STFC UWB scheme that we proposed for the first time in [13]. This proposed scheme allows two source nodes to cooperate with each other to send the Alamouti STFC in a distributed fashion to the destination in order to achieve higher diversity for the UWB system. The proposed scheme is demonstrated in Fig.2. Due to the limited space, the STFC construction method for MB-OFDM UWB systems will not be reviewed in this paper. Interested reader may refer to our previous publication [6, Section 3] for more detail. We consider the application of the Alamouti STFC [6],[14]

$$S = \begin{bmatrix} \bar{s}_{A_i} & \bar{s}_{B_i} \\ -\bar{s}_{B_i}^* & \bar{s}_{A_i}^* \end{bmatrix} \quad (1)$$

For the ease of explanation, we first consider the case where the STFC symbols  $\bar{s}_{A_i}$  and  $\bar{s}_{B_i}$  are the column vectors that consist of the original modulated data (i.e. before the IFFT operation) and correspond to the  $i$ -th MB-OFDM symbol transmitted by the nodes  $A$  and  $B$ , respectively. It is assumed that nodes in the system are perfectly synchronized. Denote  $\bar{h}_{jk} = [h_{jk,1}, h_{jk,2}, \dots, h_{jk,L_{jk}}]^T$  to be the channel vector between the two nodes  $j$  and  $k$ , where  $j \in \{A, B\}$ ,  $k \in \{A, B, d\}$  (see Fig.2), and  $L_{jk}$  is the number of multipaths in this channel. The channels between nodes are modeled as independent log-normally distributed random variables (RVs) [7] and the channel vectors  $\bar{h}_{jk}$  are assumed to be constant during every two MB-OFDM symbol time slots. The channel coefficients are assumed to be known at the destination node. Each of the source nodes  $A$  and  $B$  and the destination node  $d$  are equipped with only one antenna for transmitting and receiving signals. In the cooperative communication, each source node transmits its own data as well as performs as a cooperative agent for other nodes.

In the 2-OCCS, two nodes are paired to cooperate with one another. At the first MB-OFDM symbol time slot, Node  $A$  broadcasts its symbol  $\bar{s}_{A_i}$  to the destination node  $d$  as well as its partner (Node  $B$ ). Simultaneously, Node  $B$  also broadcasts its symbol  $\bar{s}_{B_i}$  to its partner node  $A$  and the destination node  $d$ . We denote the decoded symbols at Nodes  $A$  and  $B$  to be  $\bar{\tilde{s}}_{B_i}$  and  $\bar{\tilde{s}}_{A_i}$ . In the second MB-OFDM time slot, these two source nodes retransmit the decoded symbols to the destination in the form of  $-\bar{\tilde{s}}_{B_i}^*$  and  $\bar{\tilde{s}}_{A_i}^*$ , respectively. The process continues until all data are transmitted. This proposed scheme is thus referred to as decode-and-forward scheme [12]. This scheme is simpler than some of the existing cooperative communication schemes, such as [17], [18], with the penalty of losing the flexible cooperation level between two nodes.

After the overlap-and-add operation (OAAO) [4], [6] and FFT have been performed, the signals received at the destination node  $d$  during the two time slots can be represented as

$$\begin{aligned}\bar{\mathbf{r}}_1 &= \bar{\mathbf{h}}_{Ad} \bullet \bar{s}_{A_i} + \bar{\mathbf{h}}_{Bd} \bullet \bar{s}_{B_i} + \bar{\mathbf{n}}_1 \\ \bar{\mathbf{r}}_2 &= -\bar{\mathbf{h}}_{Ad} \bullet \bar{s}_{B_i}^* + \bar{\mathbf{h}}_{Bd} \bullet \bar{s}_{A_i}^* + \bar{\mathbf{n}}_2\end{aligned}\quad (2)$$

where  $\bar{h}_{jk} = FFT(\bar{h}_{jk})$ ,  $\bar{\mathbf{n}}_t = FFT(\bar{n}_t)$ , while  $\bar{n}_t$  ( $t=1,2$ ) denotes the column vector of complex Gaussian noise affecting the destination node at the  $t$ -th MB-OFDM symbol time slot. Denote  $\bar{h}_{jk} = [\bar{h}_{jk,1}, \bar{h}_{jk,2}, \dots, \bar{h}_{jk,N_g}]^T$  and  $\bar{\mathbf{r}}_t = [\bar{r}_{t,1}, \bar{r}_{t,2}, \dots, \bar{r}_{t,N_g}]^T$ . Once the destination node receives the symbols transmitted during the two time slots, it is able to decode the symbols.

If we assume theoretically that the transmission between the source nodes can be error-free decoded by their partners, i.e.  $\bar{s}_{A_i} \equiv \bar{s}_{A_i}$  and  $\bar{s}_{B_i} \equiv \bar{s}_{B_i}$ , the symbols can be decoded by the maximum likelihood (ML) decoding in [6]. In the proposed system, each of the two MB-OFDM symbols  $\bar{s}_{A_i}$  and  $\bar{s}_{B_i}$  can be decoded separately, rather than jointly. Furthermore, each individual modulated symbol (among  $N_D$  symbols) within symbol  $\bar{s}_{A_i}$  (or  $\bar{s}_{B_i}$ ) can be decoded separately, rather than the whole  $N_D$  data are decoded simultaneously. Thus the decoding process is completely linear, and relatively simple. In particular, the decoding metrics for data at the  $n$ -th subcarrier, for  $n = 1, \dots, N_D$ , in the MB-OFDM symbols  $\bar{s}_{A_i}$  and  $\bar{s}_{B_i}$  are

$$s_{A_i,n} = \arg \min_{s \in C} \left\{ \left| \left( \bar{h}_{Ad,n}^* \bar{\mathbf{r}}_{1,n} + \bar{h}_{Bd,n} \bar{\mathbf{r}}_{2,n}^* \right) - s \right|^2 + \left[ -1 + \left( \left| \bar{h}_{Ad,n} \right|^2 + \left| \bar{h}_{Bd,n} \right|^2 \right) \right] |s|^2 \right\} \quad (3)$$

$$s_{B_i,n} = \arg \min_{s \in C} \left\{ \left| \left( \bar{h}_{Bd,n}^* \bar{\mathbf{r}}_{1,n} - \bar{h}_{Ad,n} \bar{\mathbf{r}}_{2,n}^* \right) - s \right|^2 + \left[ -1 + \left( \left| \bar{h}_{Ad,n} \right|^2 + \left| \bar{h}_{Bd,n} \right|^2 \right) \right] |s|^2 \right\}$$

In order to achieve the full duplex capability of the cooperative nodes (i.e. transmit and receive the message at the same time), a code division multiple access (CDMA) was proposed in [18] [19]. This technique assigned a unique spreading code to each node, thus two nodes can work in the same band. However, in this proposed system model, we took advantage of the important technical specification of MB-OFDM UWB devices that, support for the first band group (3168 – 4752 MHz, see [4], Table 7-1) is mandatory, and that the Time Frequency Code (TFCs) numbers 5, 6 and 7 for the first band group are non-overlapped with each other (See [4] Table 7-2). Thus, in order for the nodes to be able to transmit their own data and receive the partner's data at the same time via only one antenna, Node  $A$  may, for instance, transmit signals by using TFC 5 (i.e. the radio frequency (RF) is in the range 3168 – 3696 MHz corresponding to the subband 1). Similarly, Node  $B$  may transmit signals by using TFC 6. The destination node must be able to work with all the subbands 1 and 2. This example is shown in Fig. 3. The principle of transmitting information in one frequency band and receiving information in another frequency band has been widely implemented, such as

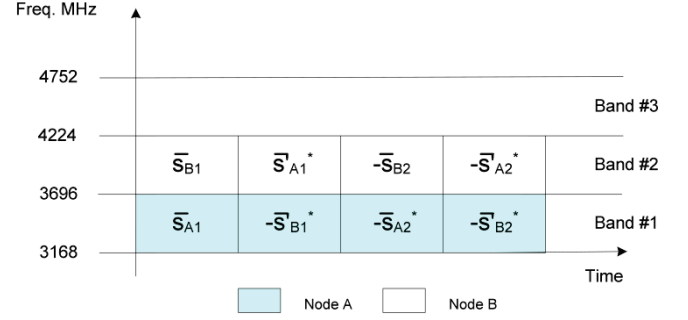


Fig.3. Subband allocation in the 2-OCCS

at the transponders in satellite communications. A node informs other nodes about its TFC by broadcasting its TFC in the 3-bit TX TFC field (bits T1 –T3) within the PHY (Physical Layer) header [4, p.28].

It has been shown from the 2-OCCS design in [13] that it is possible to apply cooperative communication to the STFC MB-OFDM system. The Alamouti STFC provides better error performance for the system in various cases. However, if we can cooperate more source nodes in the STFC MB-OFDM system using order-4 orthogonal STFCs, the performance improvement is even better for the same transmission power and data rate. Also, the error performance can be further improved if the destination is equipped with multiple receive antennas. This paper thus proposes an Order-4 Orthogonal Cooperative Communication STFC scheme, referred to as 4-OCCS.

### III. ORDER-4 ORTHOGONAL COOPERATIVE COMMUNICATION SCHEME (4-OCCS)

To achieve a higher diversity order, we consider the application of the following rate-3/4 Orthogonal STFC, which in turns the STFC version of the rate-3/4 code in [16], to enable four single-antenna source nodes to cooperate

$$S = \begin{bmatrix} \bar{s}_{A_i} & \bar{s}_{B_i} & \bar{s}_{C_i} & 0 \\ -\bar{s}_{B_i}^* & \bar{s}_{A_i} & 0 & \bar{s}_{C_i} \\ -\bar{s}_{C_i}^* & 0 & \bar{s}_{A_i} & -\bar{s}_{B_i} \\ 0 & -\bar{s}_{C_i} & \bar{s}_{B_i} & \bar{s}_{A_i} \end{bmatrix} \quad (4)$$

where the STFC symbols  $\bar{s}_{A_i}$ ,  $\bar{s}_{B_i}$  and  $\bar{s}_{C_i}$  are considered as the column vectors that consist of the original transmitted data (i.e. before the  $IFFT$  operation) and correspond to the  $i$ -th MB-OFDM symbol by the nodes  $A$ ,  $B$  and  $C$  respectively in the first time slot. It is assumed that the nodes in the proposed system are perfectly synchronized.

Denote  $\bar{h}_{jkm} = [h_{jkm,1}, h_{jkm,2}, \dots, h_{jkm,L_{jkm}}]^T$  to be the channel vector between two nodes  $j$  and  $k$ , at the  $m$ -th antenna of the destination node, where  $j \in \{A, B, C, D\}$ ,  $k \in \{A, B, C, D, d\}$ ,  $m \in \{1, 2, \dots, N\}$  and  $L_{jkm}$  represents the number of multipath in this link. The channels between nodes are modeled as independent log-normally distributed RVs [7] and we assumed the channel vectors  $\bar{h}_{jkm}$  remain constant during every four



TABLE I

4-OCCS DECODING METRICS PSK OR QAM MODULATON

Symbol	Decoding Metric
$\bar{s}_{A_i}$	$\arg \min_{s \in C} \left\  \left\{ \sum_{m=1}^N (h_{Adm}^* \bullet \bar{c}_{1m} + h_{Bdm} \bullet \bar{c}_{2m}^* + h_{Cdm} \bullet \bar{c}_{3m}^* + h_{Ddm}^* \bullet \bar{c}_{4m}) - \bar{s} \right\} \right\ ^2 + \left[ -1 + \sum_{m=1}^N ( h_{Adm}  \cdot \wedge 2 +  h_{Bdm}  \cdot \wedge 2 +  h_{Cdm}  \cdot \wedge 2 +  h_{Ddm}  \cdot \wedge 2) \right] \cdot ( \bar{s}  \cdot \wedge 2) \right\ _F^2$
$\bar{s}_{B_i}$	$\arg \min_{s \in C} \left\  \left\{ \sum_{m=1}^N (h_{Bdm}^* \bullet \bar{c}_{1m} - h_{Adm} \bullet \bar{c}_{2m}^* - h_{Ddm} \bullet \bar{c}_{3m}^* + h_{Cdm}^* \bullet \bar{c}_{4m}) - \bar{s} \right\} \right\ ^2 + \left[ -1 + \sum_{m=1}^N ( h_{Adm}  \cdot \wedge 2 +  h_{Bdm}  \cdot \wedge 2 +  h_{Cdm}  \cdot \wedge 2 +  h_{Ddm}  \cdot \wedge 2) \right] \cdot ( \bar{s}  \cdot \wedge 2) \right\ _F^2$
$\bar{s}_{C_i}$	$\arg \min_{s \in C} \left\  \left\{ \sum_{m=1}^N (h_{Adm}^* \bullet \bar{c}_{1m} + h_{Bdm} \bullet \bar{c}_{2m}^* + h_{Cdm} \bullet \bar{c}_{3m}^* + h_{Ddm}^* \bullet \bar{c}_{4m}) - \bar{s} \right\} \right\ ^2 + \left[ -1 + \sum_{m=1}^N ( h_{Adm}  \cdot \wedge 2 +  h_{Bdm}  \cdot \wedge 2 +  h_{Cdm}  \cdot \wedge 2 +  h_{Ddm}  \cdot \wedge 2) \right] \cdot ( \bar{s}  \cdot \wedge 2) \right\ _F^2$

MB-OFDM symbol time slots, and are known at the destination node. Each of the source nodes  $A$ ,  $B$ ,  $C$  and  $D$  is equipped with only one antenna for transmitting and receiving signals, while the destination node  $d$  might be equipped with  $N$  antennas.

The transmission protocol in the proposed 4-OCCS is presented in Fig. 4. One may have a question: Does the four source nodes need to occupied four subbands in the cooperative MB-OFDM UWB system to work properly? From Eq. (4), it is clear that, in the proposed system, three nodes transmit three MB-OFDM symbols over their three antennas and there is always one source node remaining idle in every time slot. Thus in 4-OCCS, we propose a new subband allocation method that allows the system to work properly by occupying just three subbands in the first band group of MB-OFDM UWB. Again, it is noted that MB-OFDM UWB devices must support for the first band group (3168 – 4752 MHz) [4, Table 7-1], and that the TFC numbers 5, 6 and 7 for the first band group are non-overlapped with each other [4, Table 7-2]. In order for the system to work properly by just taking three subbands, the source nodes  $A$ ,  $B$  and  $C$  in the proposed system must be able to transmit data in one certain subband and receive data in other two subbands. The source node  $D$  must able to transmit and receive the data using all subbands in the first band group.

Node A	$\bar{s}_{A1}$	$-\bar{s}_{B1}^*$	$-\bar{s}_{C1}^*$	0	$\bar{s}_{A2}$	$-\bar{s}_{B2}^*$	.....
Node B	$\bar{s}_{B1}$	$\bar{s}_{A1}^*$	0	$-\bar{s}_{C1}^*$	$\bar{s}_{B2}$	$\bar{s}_{A2}^*$	.....
Node C	$\bar{s}_{C1}$	0	$\bar{s}_{A1}^*$	$\bar{s}_{B1}^*$	$\bar{s}_{C2}$	0	.....
Node D	0	$\bar{s}_{C1}$	$-\bar{s}_{B1}$	$\bar{s}_{A1}$	0	$\bar{s}_{C2}$	.....

Decode  $\bar{s}_{A1}$ ,  $\bar{s}_{B1}$  &  $\bar{s}_{C1}$

Fig.4. Transmission protocol in 4-OCCS

In Fig.5, we proposes a new subband allocation for the four cooperative nodes. Node  $A$  transmits signals using TFC 7 (RF is in the range 4224 - 4752 MHz corresponding to the subband 3) and receive signals using TFC 6 (RF in the range 3696 – 4224 MHz, subband 2) and TFC 5 (3168 – 3696 MHz, subband 1). Node  $B$  transmits signals using TFC 6 and receive signals using TFC 5 and TFC 7. Node  $C$  transmits signals using TFC 5 and receive via TFC 6 and TFC 7. Node  $D$  transmits signals in the subband 1, 2 and 3 sequentially, i.e. this node uses TFC 1 when transmitting, and receives data from all the subbands. The destination node must be able to receive signals from all subbands in the first band group.

Detail of how the nodes transmit signals in the proposed system is explained as follows. In the 4-OCCS, four nodes cooperate in sending the orthogonal matrix in (4) to the destination. The issue of how this node quadruple is selected among the nodes in the network is out of the scope of this paper. Instead, this paper addresses the full-duplex cooperative communications scheme for this quadruple and the decoding method.

As shown in Fig.4 and Fig.5, in the first time slot, Nodes  $A$ ,  $B$  and  $C$  broadcast the MB-OFDM symbols,  $\bar{s}_{A_i}$ ,  $\bar{s}_{B_i}$  and  $\bar{s}_{C_i}$  to all the nodes in the system in the subbands 3, 2 and 1 respectively, while Node  $D$  does not transmit, but just receives the data from these three nodes in three different subbands. After first time slot, every node will received at least two MB-OFDM symbols from their partners. The received data can be distinguished by different subbands. We denote the decoded symbols at each nodes to be  $\bar{s}_{A_i}$ ,  $\bar{s}_{B_i}$  and  $\bar{s}_{C_i}$ . In second time slot, Nodes  $A$ ,  $B$  and  $D$  transmit the decoded MB-OFDM symbol  $-\bar{s}_{B_i}^*$ ,  $\bar{s}_{A_i}^*$  and  $\bar{s}_{C_i}$  to the destination in the subbands 3, 2 and 1 respectively. Node  $D$  occupies the subband 1 because Node  $C$  is silent in the second time slot. In third time slot, Node  $B$  keeps silent while Node  $A$ ,  $C$  and  $D$  transmit the data  $-\bar{s}_{C_i}^*$ ,  $\bar{s}_{A_i}^*$  and  $-\bar{s}_{B_i}$  to the destination node  $d$  in the subbands 3, 1 and 2 respectively. Node  $D$  occupies the subband 2 since Node  $B$  is silent. In the fourth time slot, Node  $B$ ,  $C$  and  $D$  transmit the data  $-\bar{s}_{C_i}^*$ ,  $\bar{s}_{B_i}^*$  and  $\bar{s}_{A_i}$  to the destination in the subbands 2, 1 and 3 respectively. Node  $D$  occupies the subband 3 since Node  $A$  is silent. The destination is able to decode the MB-OFDM symbol  $\bar{s}_{A_i}$ ,  $\bar{s}_{B_i}$  and  $\bar{s}_{C_i}$  after four time slots. The decoding procedure is presented as follows.

After the overlap-and-add operation (OAAO) [4],[6] and FFT have been performed, the signals received at the  $m$ -th Rx antenna at the destination node during the four time slots can be represented as

$$\begin{aligned}
\bar{\mathbf{r}}_{1m} &= \bar{\mathbf{h}}_{Adm} \bullet \bar{s}_{A_i} + \bar{\mathbf{h}}_{Bdm} \bullet \bar{s}_{B_i} + \bar{\mathbf{h}}_{Cdm} \bullet \bar{s}_{C_i} + \bar{\mathbf{n}}_{1m} \\
\bar{\mathbf{r}}_{2m} &= -\bar{\mathbf{h}}_{Adm} \bullet \bar{s}_{B_i}^* + \bar{\mathbf{h}}_{Bdm} \bullet \bar{s}_{A_i}^* + \bar{\mathbf{h}}_{Ddm} \bullet \bar{s}_{C_i} + \bar{\mathbf{n}}_{2m} \\
\bar{\mathbf{r}}_{3m} &= -\bar{\mathbf{h}}_{Adm} \bullet \bar{s}_{C_i}^* + \bar{\mathbf{h}}_{Cdm} \bullet \bar{s}_{A_i}^* - \bar{\mathbf{h}}_{Ddm} \bullet \bar{s}_{B_i} + \bar{\mathbf{n}}_{3m} \\
\bar{\mathbf{r}}_{4m} &= -\bar{\mathbf{h}}_{Bdm} \bullet \bar{s}_{C_i}^* + \bar{\mathbf{h}}_{Cdm} \bullet \bar{s}_{B_i}^* + \bar{\mathbf{h}}_{Ddm} \bullet \bar{s}_{A_i} + \bar{\mathbf{n}}_{4m}
\end{aligned} \quad (5)$$

where  $\bar{\mathbf{h}}_{jkm} = FFT(\bar{h}_{jkm})$ ,  $\bar{\mathbf{n}}_{tm} = FFT(\bar{n}_{tm})$ , while  $\bar{\mathbf{n}}_{tm}$  ( $t=1,2,3,4$ ) denotes the column vector of complex Gaussian noise affecting the  $m$ -th antenna of the destination node at  $t$ -th MB-OFDM symbol time slot. Denote  $\bar{\mathbf{h}}_{jkm} = [\bar{h}_{jkm,1}, \bar{h}_{jkm,2}, \dots, \bar{h}_{jkm,N_{gi}}]^T$  and  $\bar{\mathbf{r}}_{tm} = [\bar{r}_{tm,1}, \bar{r}_{tm,2}, \dots, \bar{r}_{tm,N_{gi}}]^T$ . We also assume that the information transmitted from the source nodes can be error-free decoded by their partners as mentioned in Section II, i.e.  $\bar{s}_{A_i} \equiv \bar{s}_{A_i}$ ,  $\bar{s}_{B_i} \equiv \bar{s}_{B_i}$  and  $\bar{s}_{C_i} \equiv \bar{s}_{C_i}$ . The ML decoding will be applied to decode the symbols. In the proposed system, each of the MB-OFDM symbols  $\bar{s}_{A_i}$ ,  $\bar{s}_{B_i}$  and  $\bar{s}_{C_i}$  can be decoded separately, rather than jointly, thanks to the orthogonality of the code matrix (4). More importantly, each among  $N_D$  data within each MB-OFDM symbol can also be separately decoded, rather than decoding the whole  $N_D$  data simultaneously. For  $n=1, \dots, N_D$ , the decoding process for the  $n$ -th subcarrier in MB-OFDM symbols  $\bar{s}_{A_i}$ ,  $\bar{s}_{B_i}$  and  $\bar{s}_{C_i}$  are

$$\begin{aligned}
s_{A_i,n} &= \arg \min_{s \in C} \left\{ \left| \sum_{m=1}^N (\bar{h}_{Adm,n}^* \bar{r}_{1m,n} + \bar{h}_{Bdm,n}^* \bar{r}_{2m,n} + \bar{h}_{Cdm,n}^* \bar{r}_{3m,n} + \bar{h}_{Ddm,n}^* \bar{r}_{4m,n}) - s \right|^2 \right. \\
&\quad \left. + \left[ -1 + \sum_{m=1}^N (|\bar{h}_{Adm,n}|^2 + |\bar{h}_{Bdm,n}|^2 + |\bar{h}_{Cdm,n}|^2 + |\bar{h}_{Ddm,n}|^2) \right] |s|^2 \right\} \\
s_{B_i,n} &= \arg \min_{s \in C} \left\{ \left| \sum_{m=1}^N (\bar{h}_{Bdm,n}^* \bar{r}_{1m,n} - \bar{h}_{Adm,n}^* \bar{r}_{2m,n} - \bar{h}_{Ddm,n}^* \bar{r}_{3m,n} + \bar{h}_{Cdm,n}^* \bar{r}_{4m,n}) - s \right|^2 \right. \\
&\quad \left. + \left[ -1 + \sum_{m=1}^N (|\bar{h}_{Adm,n}|^2 + |\bar{h}_{Bdm,n}|^2 + |\bar{h}_{Cdm,n}|^2 + |\bar{h}_{Ddm,n}|^2) \right] |s|^2 \right\} \\
s_{C_i,n} &= \arg \min_{s \in C} \left\{ \left| \sum_{m=1}^N (\bar{h}_{Cdm,n}^* \bar{r}_{1m,n} - \bar{h}_{Adm,n}^* \bar{r}_{3m,n} + \bar{h}_{Ddm,n}^* \bar{r}_{2m,n} - \bar{h}_{Bdm,n}^* \bar{r}_{4m,n}) - s \right|^2 \right. \\
&\quad \left. + \left[ -1 + \sum_{m=1}^N (|\bar{h}_{Adm,n}|^2 + |\bar{h}_{Bdm,n}|^2 + |\bar{h}_{Cdm,n}|^2 + |\bar{h}_{Ddm,n}|^2) \right] |s|^2 \right\}
\end{aligned} \quad (6)$$

In fact, the nodes may have errors when they decode the received signals from their partners, i.e.  $\bar{s}_{A_i} \neq \bar{s}_{A_i}$ ,  $\bar{s}_{B_i} \neq \bar{s}_{B_i}$  and  $\bar{s}_{C_i} \neq \bar{s}_{C_i}$ , thus performance of the proposed system will be effected by not only the decoding process at the destination node, but also the decoding process at the source nodes. Intuitively, when the decoding errors in the source nodes become serious, they may ruin the advantage of higher transmission diversity that is brought by the cooperative communication.

The inherent design of MB-OFDM UWB devices provides an important feature that it might have already allowed the devices to work with different TFCs (i.e. different subbands) in the first band group. Consequently, in order to implement the proposed system, we only need to make the source nodes  $A$ ,  $B$  and  $C$  be able to transmit signals in one subband, and receive signals in two other subbands simultaneously, while making the source node  $D$  and the destination node be able to receive signals from all three subbands in the first band group at the same time. These are not very hassling tasks thanks to

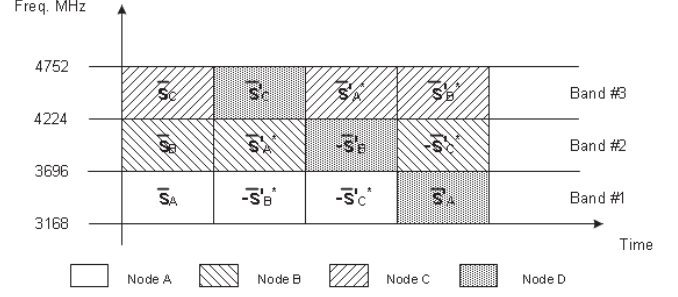


Fig. 5. Subband allocation in 4-OCCS in four time slots

the implementation of precise filters. As a result, the design of transmitter/receiver at nodes can be created by modifying their current design without additional heavy complexity.

#### IV. SIMULATION RESULTS

To examine the performance advantage of cooperative communication, we ran several Monte-Carlo simulations for non-cooperative communication and for the 2-OCCS and the 4-OCCS. Each run of simulations was carried out with 1200 MB-OFDM symbols. One hundred channel realizations of each channel model (CM1 to CM4) were considered for the transmission of each MB-OFDM symbol. In simulations, SNR is defined to be the signal-to-noise ratio (dB) per sample in a MB-OFDM symbol, at each Rx antenna (i.e. the subtraction between the total power (dB) of the received signal corresponding to the sample of interest and the power of noise (dB) at that Rx antenna).

In order to fairly compare the error performance of non-cooperative and the two cooperative communication schemes, the following constraints are applied to all simulations.

**Data rate constraint:** Different signal constellation mapping (QPSK/DCM) schemes are applied to guarantee that the simulations for all three systems are run with the same bit rate. In particular, the conventional MB-OFDM UWB and 2-OCCS uses 8-PSK while the rate-3/4 4-OCCS uses 16QAM.

**Power constraint:** The total received power at each Rx antenna at the destination during each time slot need to be the same in all systems. Therefore, the signal constellation points in the 2-OCCS (cf. Eq.(1)) are scaled down by a factor of  $1/\sqrt{2}$ , while the factor is  $1/\sqrt{3}$  for the case of 4-OCCS (cf. Eq.(4)).

Fig.6 compares the error performances of the conventional MB-OFDM (non-cooperative), 2-OCCS and 4-OCCS in the case where all nodes are equipped with one antenna. From Fig. 6, it is clear that the 4-OCCS scheme provides significantly better error performance than the 2-OCCS scheme and the conventional system in the channel models CM 1, CM2 and CM3. The performances of the two cooperative systems are relatively close to each other in the channel model CM4 due to the fact that the channel is extremely dispersive, causing a serious inter-symbol interference problem that neutralizes the diversity advantage of the order-4 cooperative communication, compared to the order-2 one.

Fig.7 demonstrates the error performances of three systems in the case the destination node is equipped with 2 Rx antennas. From Fig.7, the overall error performance of the proposed

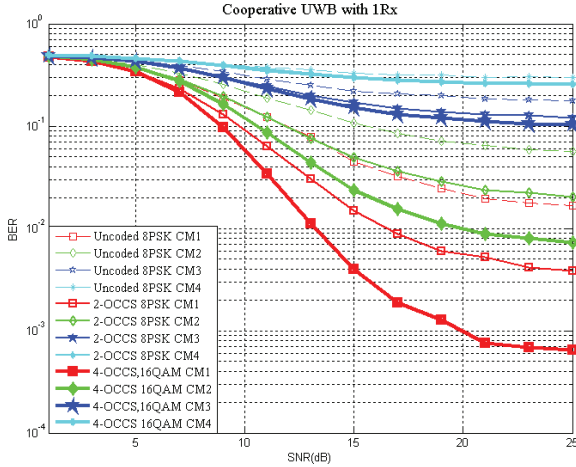


Fig.6. 4-OCCS vs. 2-OCCS vs. Conventional MB-OFDM UWB with one-antenna destination node

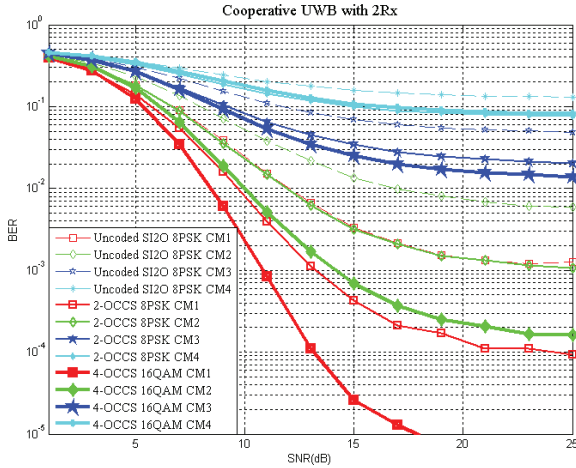


Fig.7. 4-OCCS vs. 2-OCCS vs. Conventional MB-OFDM UWB with two-antenna destination node

system is significantly improved owing to the higher diversity produced by the multiple antennas at the receiver. As the result, the 4-OCCS provides much better error performances than the 2-OCCS in the channel models CM1, 2 and 3.

## V. CONCLUSIONS

This paper has proposed an Order-4 Orthogonal STFCs cooperative communication scheme in MB-OFDM UWB, referred to as the 4-OCCS. From the simulation results, we might conclude that, with the same transmission power and data rate, the error performance of the 4-OCCS is significantly better, compared to the conventional MB-OFDM UWB in all channel models. The simulation results also prove that the 4-OCCS might be significantly better than the 2-OCCS in the channel model CM 1, 2 or 3 without significant additional decoding complexity.

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